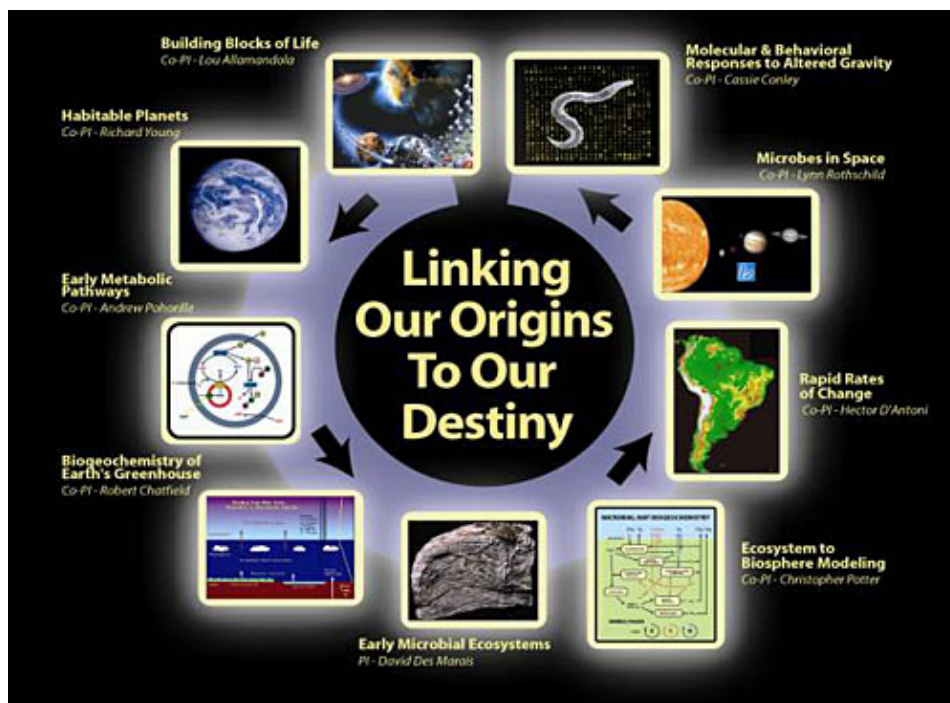


Project Report: Delivery of Organic Materials to Planets

Ames Research Center
Executive Summary
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Piecing together the history of life -- its origins, evolution, and continuation -- is a function of identifying and gaining insight into the processes and conditions, cosmic and terrestrial, that support organic systems. It means, for example, learning, through observation, experimentation, and computer modeling, how carbon compounds evolved, how biologically significant molecules formed, how primitive cells developed, how bacteria arose and flourished, how proteins evolved, and how Earth-based life forms are affected by environmental changes and how adaptable and survivable they might be if subjected to the more rigorous environments of space.

The Ames team addresses a wide range of disciplines that focus on the context for life, the origin and early evolution of life, and the future of life.



Context for Life. The chemistry and the environments conducive to life's origin are investigated. The cosmic evolution of carbon compounds is traced, spectroscopically and chemically, from the interstellar medium to protoplanetary nebulae, planetesimals, and finally onto habitable bodies. The

history of abiotically produced molecules of biological significance is probed. These investigations rely on spectral and chemical studies of realistic laboratory analogs tightly coupled with quantum chemical calculations followed by astronomical searches.

This year, we clearly demonstrated that compounds having biological significance can form in cosmic ices. We also showed that true membrane-forming molecules can form under simulated space conditions, and that the molecules that are formed indeed produce true vesicles that have penetrable membrane walls. It was demonstrated that the most common amino acids employed in living systems can be produced under conditions found in deep space, and we also found that a much broader array of polycyclic aromatic hydrocarbons (PAHs) can be produced under these conditions. A peer-reviewed literature publication that described our studies of amino acid production under interstellar conditions generated considerable public interest.

The habitability of planets was investigated by identifying and quantifying those factors that collectively determine the inner and outer limits of the circumstellar habitable zone. For example, (1) water must have been delivered to the planet; and (2) climatic conditions must allow surface liquid water to persist. The focus is on the origin and physical state of water, a study that depends on the sources of the water, the cycling of water and other volatiles between the surface and interior of a planet, and the detailed climate of the planet.

Computer simulations of planetary accretion were used in an investigation of the likelihood that Earth-like planets exist in orbit around stars similar to the Sun. It was found that terrestrial planets should form in orbit around Sun-like stars, provided that a star's protoplanetary nebula and giant planets are somewhat similar to those of the Solar System. However, Earth-like planets do not form if the planetary system has giant planets that have orbital periods of less than a few years, or if their orbits are either highly inclined or highly eccentric.

More accurate stratospheric temperature profiles were developed using a new computational method for calculating infrared fluxes for our radiative-convective climate model. The absorption spectra for carbon dioxide (CO₂) and water (H₂O) are now parameterized using more precise 16-term correlated k coefficient sums that provide a better resolution of the Doppler cores of the absorption lines.

Through a combination of laboratory studies and numerical modeling, we have demonstrated that CO₂ clouds are unlikely to have provided a significant greenhouse warming effect during the early history of Mars. Accordingly, the current greenhouse model that has been proposed to explain the formation of ancient river valleys on Mars is seriously flawed.

Data from the Clouds and Earth's Radiant Energy System (CERES) instrument onboard the Earth Observing System (EOS) satellites provide insights into the development of runaway greenhouse conditions in a planetary atmosphere.

The outgoing infrared (IR) radiative energy flux first maximizes, then decreases, as a function of increasing sea surface temperature (SST). This is a signature of a runaway greenhouse effect. A clear distinction exists between the maximum SST and the SST at which the outgoing IR flux attains a maximum value. There is also a strong inverse correlation between the magnitude of the outgoing IR flux and the quantity of water vapor above an altitude of 5 km (16,400 ft).

Origin and Early Evolution of Life and Its Biosignatures. A hypothesis that the most primitive protocells were structures built of evolving components that are related to those present in contemporary cells, but functioning without genomic control, is being tested. Simple biomolecular systems that are capable of performing essential cellular functions are being defined and conditions under which they can work together in a cellular environment will be determined.

We developed a technology for in vitro protein evolution known as messenger-RNA (mRNA) display, and have recently selected for functional proteins that bind adenosine triphosphate (ATP), starting from a very large library of random sequences. These proteins have a high selectivity for ATP over guanosine triphosphate (GTP) or cyclic ATP, and they exhibit a high selectivity for zinc (Zn) ions and not magnesium (Mg) ions. Because these novel proteins have very low folding energies, they are easily unfolded and trapped in nonfunctional conformations. We have evolved variants of one of these ATP-binding proteins that demonstrate more stable folded structures.

Early microbial ecosystems are being investigated by combining the results of paleohistorical studies with experimental investigations of representative contemporary microbial ecosystems, and with model building. An improved understanding of the long-term evolution of Earth's biosphere and of the biogeochemical cycles that influence the environment will help in assessing the survival prospects of other biospheres and in developing a strategy for finding them by interpreting their biosignatures. Such biosignatures will help in our search for a potential Martian biosphere, and in recognizing possible spectroscopic signatures of inhabited planets around other stars.

Photosynthetically active hypersaline cyanobacterial mats produced a substantial hydrogen flux at night; fermentative processes are probably responsible for this hydrogen flux. Methane and reduced sulfur gases were also produced. Intertidal mats exhibited a greater hydrogen flux than subtidal mats. In the ancient low-oxygen atmosphere, this hydrogen flux would have elevated the rates of hydrogen escape to space, thus contributing to the long-term increase in the oxidation state of the global environment.

Bahamian stromatolites were examined for their rates of photosynthesis, aerobic respiration, and sulfate reduction. These rates were much lower in lithifying stromatolites than in nonlithifying hypersaline mats. However, incubations of organic substrates with slurries from the stromatolites indicated high potential rates of both aerobic respiration and sulfate reduction.

Hot-spring cyanobacterial mats were both exposed to and shielded from

ultraviolet (UV) radiation. Analyses of ribonucleic acid (RNA) indicated that cyanobacteria in both treatments were very similar. However, when later exposed to UV, the mats that had been UV-shielded exhibited lower rates of photosynthesis, perhaps reflecting different patterns of gene expression.

Hypersaline cyanobacterial mats have been maintained in an Ames' greenhouse so the effects of environmental conditions can be studied. Mats maintained for more than 1 year strongly resembled the microbial populations and key process rates of mats freshly collected from the field. A greenhouse experiment was begun to document the effects of submillimolar concentrations of sulfate on marine cyanobacterial mats; sulfate concentrations were low in ancient marine environments. Observations to date indicate that relatively minor ecological changes have occurred as sulfate concentrations have declined from hypersaline levels, that is, from more than 70 millimoles to less than 5 millimoles (>70 mM) to <5 mM).

We constructed a model to simulate carbon (C), oxygen (O), and sulfur (S) cycles, and growth of cyanobacteria and sulfur bacteria in a stratified hypersaline mat. The aim was to simulate microbial effects on the atmospheric chemistry of early Earth. Inputs to the mat system include photosynthetically active radiation (PAR), near-infrared radiation (NIR), and temperature. Attenuation of PAR with each layer is modeled; NIR attenuation depends on the abundance of bacteriochlorophyll a. The bacterial groups whose metabolism and growth are simulated include cyanobacteria (CYA), purple sulfur bacteria (PSB), colorless sulfur bacteria (CSB), and sulfur reducing bacteria (SRB). Growth of CYA occurs by either oxygenic or anoxygenic photosynthesis (AP), depending on the available substrate, oxygen or hydrogen sulfide (O_2 or H_2S). PSB growth occurs by AP using NIR and H_2S or by chemosynthesis (CH), using O_2 and H_2S . Growth of CSB occurs by means of CH, also using O_2 and H_2S . SRB growth occurs by means of anaerobic CH utilizing SO_4^{2-} and creating H_2S in the process. The model consists of 10 layers (1 mm each), and gains density as biomass increases. Gas diffusion occurs between successive layers. The model was constructed in a Stellatm (software) environment, and will be updated to include methanogens and decomposition before being programmed into an environment that is compatible with atmospheric simulations of early Earth.

Future of life. The effects of rapid environmental change on the properties of ecosystems are investigated. We are defining environmental factors that drive ecological changes in South America, and we also analyze preserved records of past changes for the purpose of ultimately predicting future trends.

The responses of South American vegetation to the El Nino Southern Oscillation (ENSO) are being reconstructed at 8-km spatial resolution and at 1-month time resolution. Because SST is an important driver of climate and of ENSO, we have reconstructed past SSTs of the Atlantic and Pacific Oceans for the time period 1246 to 1991, using tree-ring data for South America that have been processed by using neural network methods.

The potential for the survival and evolution of Earth-based life beyond its planet of origin is being explored, and the effects of various forms of radiation

on the survival of life in extreme environments, including those of space, are being documented. Our work includes developing methods for assessing radiation damage, examining specific biota for radiation resistance, and exposure experiments that include spaceflight.

Several halophilic microorganisms have been isolated from nature and tests begun of their resistance to radiation. Dozens of strains of *Dunaliella salina*, an extremely halophilic alga, have been tested for resistance to oxidative damage. (Halophilic organisms thrive in salty environments.) Parallel studies have also begun with tardigrades and brine shrimp.

A halophilic *Synechococcus* cyanobacterium, *Deinococcus radiodurans*, and several halophilic archaea have been exposed to both vacuum desiccation and UV irradiation in the space-simulation facility at the DLR in Cologne, Germany. Interestingly, the cyanobacterium and the archaea demonstrated much greater resistance to desiccation and UV than did *Deinococcus radiodurans*. Indeed, the cyanobacterium and the archaea can survive such exposure for at least 6 months and probably longer.

Professional Development, Education, and Public Outreach. NASA Ames astrobiology supports a variety of activities specifically focused on the needs and interests of the nation's educators, students, and the American public in general. In an effort to reach K-14 classrooms, we have developed advisory science panels, which are development teams that include the science team and participants in the professional development programs. Science review panels are organized to ensure that the products developed appropriately represent the astrobiological research, and that they will meet the national standards and serve the education community. Because distribution is key, the NASA organization is used to distribute the products to selected groups, including underrepresented minorities, publishers, websites, and national organizations in order to provide professional development and distribution of astrobiology materials. The Ames astrobiology team focuses on the general public by hosting a diverse group of visitors as they tour of the greenhouses, where lectures and group discussions take place. Our researchers contribute to the professional development of National Research Fellows, postdoctoral research staff, graduate students, interns, and Astrobiology Academy students while offering research opportunities in astrobiology at Ames. We have organized unique partnerships with internal and external organizations to provide collaborative astrobiology projects that have high visibility to ensure that they reach the general public.



During the past year, a cooperative project was undertaken with Yellowstone National Park that will enable the Park to serve as a means by which the public can explore the science and experience the excitement of astrobiology. The large number of tourists who visit Yellowstone creates a potentially effective venue for public outreach for astrobiology. Yellowstone provides a natural setting for learning about thermal-spring environments, which are of fundamental importance to an understanding of the early evolution of life on Earth, and to the search for evidence of past habitable environments and, potentially, life, on Mars. A series of educational products are envisioned, including trail signs, brochures, and contributions to the Yellowstone Resources and Issues Guide, all of which will describe the significance of Park features for astrobiology. Ultimately it might be possible to integrate astrobiological themes into permanent exhibits to be developed for the major visitor centers within the Park.